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Vliv anizotropie na fyzikální a mechanické vlastnosti hornin

Autoreferát disertační práce

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Abstrakt

Disertační práce je zaměřena především na studium anizotropie základních mechanických a fyzikálních vybraných hornin. Studie byla provedena v laboratorních podmínkách s cílem testovat variabilitu vlastností hornin a jejich vzájemné vztahy. Pro pochopení vlivu anizotropního charakteru hornin na jejich fyzikální a mechanické vlastnosti byly realizována série následujících měření a analýz: měření velikosti horninových zrn, rychlosti šíření ultrazvukových vln, měření permeability pro kapaliny, zkoušky pevnosti v prostém tlaku, brazilská zkouška, zkoušky lomové houževnatosti a triaxiální pevnosti. Testovány byly 4 typy anizotropních hornin.

Pro dosažení výše uvedeného cíle byly odebrány vzorky sedimentárních, metamorfovaných a magmatických hornin z lokalit na různých kontinentech (Česká republika, Japonsko, Jižní Korea, Jižní Afrika. Na každém z vybraných vzorků byly definovány základní osy anizotropie, označení jako Axis-1, Axis-2 and Axis-3. Roviny kolmé ke každé z os byly definovány jako Plane-1, Plane-2 and Plane-3. Pro účely této práce byla obdobně definována i použitá válcová tělesa, získaná orientovaným jádrovým vrtáním horninových bloků. Tělesa vrtaná kolmo na vrstevnatost nebo foliaci byla označena jako Type-1 and tělesa vrtaná paralelně, jako Type-3.

Anizotropie stavby hornin, daná orientací zrn a mikrotrhlin, byla úspěšně vyhodnocena na mikroskopických výbrusech odebraných z horninových bloků ve třech navzájem kolmých rovinách. K tomu byl použit optický polarizační mikroskop. Anizotropie hornin byla vyšetřována také metodou měření rychlosti šíření ultrazvukových vln materiálem, kde byly určeny rozdíly v rychlosti ultrazvuku ve třech definovaných směrech. Výsledky z ultrazvukových testů jsou v dobré korelaci s měřením orientace zrn a mikrotrhlin.

Permeabilita byla měřena na všech vzorcích za konstantního bočního tlaku 2 MPa. Byla použita válcová zkušební tělesa o průměru 50 mm a výšce 50 mm. Čas testování byl pro každý vzorek 3 hodiny. Saturace horniny byla analyzována s využitím metody rentgenové počítačové tomografie CT na zařízení TOSCANNER-20000RE). Tomografické snímky vzorků v suchém a vodou nasyceném stavu byla využity pro výpočet pórovitosti a posouzení distribuce hustot nasycení vzorku vodou. Výsledky testů permeability ukázaly pouze nevýznamné známky anisotropie.

V rámci disertační práce byly dále studovány deformační vlastnosti hornin triaxiálními zkouškami, zejména křehké a tvárné chování za mezí pevnosti za různých bočních tlaků. Byl aplikována Mohr-Coulombova teorie porušení pro různá napětí při porušení. Byly konstruovány Mohr-Coulombovy obálky pro každý z testovaných souborů těles (Type-1 a Type-3) s využitím parametrů pevnost v prostém tlaku a pevnost v tahu. Dále byla na horninách studována lomová houževnatost – mode 1 (KIC), pevnost v prostém tlaku (σc) a pevnost v tahu (σt). Byly definovány vztahy mezi KIC ku σc a σt pro určení pevnostních parametrů při porušení.

Pro pochopení vlivu anizotropie na porušování hornin v mikro i makroskopickém měřítku, byly na základě triaxiálních testů získány parametry smykové pevnosti – úhel vnitřního tření (φ) a soudržnost (c). Hodnoty těchto parametrů byly korelovány s jinými typy hornin.

Byly rovněž studovány makroskopické trhliny na zkušebních tělesech zatěžovaných asymetrickým zatížením a porušení bylo také simulováno pomocí částicových modelů (clump particle model). Ty sestávají z jednotlivých částic spojovaných do větších shluků. Modely byly kalibrovány na základě pevnostních a deformačních dat, získaných z jednoosých a trojosých zkoušek pevnosti v tlaku. V této části prezentuji významnou závislost. Celý scénář je založen na metodě diskrétních prvků (DEM), využívající kód PFC2D , vyvíjený společností ITASCA.

Jako nástroj pro analýzu chování zrnitého materiálu jsem využil PFC2D code. Výsledky ukázaly, že průběh trhlin porušení, simulovaných částicovým modelem, odpovídá zjištěným laboratorním výsledkům při různých zatíženích. Výsledky simulací také ukázaly, že v zóně porušení dominují tahové trhliny a že charakter trhlin je výrazně odlišný pro tělesa typu Type-1 a Type-3.

Prezentovaná disertační práce se detailně zabývá vlivem anizotropie hornin na jejich fyzikální a mechanické vlastnosti a studiem parametrů, získaných z testů pevnosti v prostém tlaku, pevnosti v tahu, lomové houževnatosti, triaxiální pevnosti s ohledem na hodnocení anizotropie horniny.

Práce shrnuje aktuální stav znalostí a navrhuje alternativy dalšího výzkumu do budoucnosti.

Cílem této disertační práce bylo vytvořit schéma pro hodnocení anizotropie v mechanice hornin s využitím kombinace destruktivních a nedestruktivních zkušebních metod. K dosažení tohoto cíle byly použity standardní postupy přípravy vzorků, zařízení a procedur, doporučené ISRM.

Získaná data byla zpracována pomocí sofistikovaných softwarů.

Klíčová slova: anizotropie, mechanické a fyzikální vlastnosti, pevnost v tahu, pevnost v prostém tlaku, triaxiální test, lomová houževnatost

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Content

1 Introduction

Influence of anisotropy on rock physical and mechanical properties.

One of the most important, and often frequently neglected, aspects of rock mechanics and rock engineering is that we are utilizing an existing material which is usually highly variable (J. A. Hudson et al 1997).

It is known that the physical and mechanical properties in rocks are normally affected by preferentially oriented microstructural fabric, especially microcracks, bedding planes and grain size distribution. In mining engineering, especially where rocks are subjected to tension, compression and shear, anisotropy of rock physical and mechanical properties is a major concern in studying the response of rocks for all engineering practices. It is therefore, important to understand the estimation of parameters that are influenced by anisotropy in order to solve significant problems in geo-mechanical engineering. Rock physical and mechanical properties are very important for the design of mines, rock blasting, civil engineering construction, carbon dioxide capture and storage (CCS), disposal facility of high-level nuclear waste and geotechnical engineering.

With the above mentioned applications, concerns have been drawn in understanding rock physical and mechanical properties in most research fields. There have been series of interesting research works in trying to address this issue. Some researches like, Saroglou H.,Marinos P.,and Tsiambaos G., have brought some views on the characterization of few metamorphic rocks. They focused their concern on just a single rock type (metamorphic) from a particular locality. Nasseri et al published a paper on fracture toughness of anisotropy in granitic rocks without considering other methods in the quantification of rock anisotropic properties. Also F.Dia studied the dynamic dependence of anisotropy based on micro-cracks under wide range of loading rates and his work was conducted for one granite sample and didn’t mentioned the static dependence. However, despite being an important issue in the field of geomechanics and subject to numerous studies, the problem of rock anisotropy in relation to their physical and mechanical properties has not been thoroughly defined. Many challenges still remain in full exploitation of anisotropic properties. At combined laboratory measuring conditions; including average grain diameter quantification, ultrasonic wave velocity estimation, rock permeation, UCS, anisotropic tensile test, fracture toughness, crack density propagation estimation and anisotropic testing of the traditional triaxial test provides pioneering opportunities to evaluate anisotropy properties at understandable laboratory conditions.

Determination of rock anisotropic properties which arise from rock preferential oriented micrstructural fabric, aligned heterogeneities or nonlinearity is important. They are the fundamental characteristics thought responsible for anisotropic properties of physic-mechanical properties (e.g. M.H.B Nasseri et al 2007). These inherent anisotropies with induced anisotropy during static loading rates operating at different stress systems are influencing factors in permeation, elastic, mechanical and fracture processes. Consideration of an index property scheme that can summaries all anisotropic properties is a challenging goal in the field of rock engineering.

In this thesis, I investigate a concise correlation and relationship between average grain size diameter distribution and micro-crack density distribution to results observed in ultrasonic wave speed velocities. In addition, I correlated relationships between intrinsic permeability tests for anisotropy to mechanical anisotropic response properties.

In order to report anisotropy for uniaxial compressive strength (UCS), specimens were loaded from different directions. The aim was to study the response of each specimen. Their respective maximum response to loading were averaged and compared to different specimen from the same sample. The same principle was followed for the Brazilian test and the fracture toughness test. For each test, a variety of parameters like Young's modulus, deformation modulus and peak strength for compressive strength, tensile strength and fracture toughness were determined for each specimen and their property of anisotropy is document and evaluated. I further extend my evaluation of obtained parameters to the possibilities of representing the Mohr-Coulomb criterion by using uniaxial compressive strength and tensile strength parameters which further represent anisotropy.

For analyzing the anisotropic post peak displacement of tested specimens, the traditional triaxial test was employed. Here, I focused on the post-peak force displacement energy. I analyze the post-peak behaviour in relation to its sensitivity to time effect under controlled strain rate and creep for different set of specimens in Type-1 and Type-3 conditions. For different specimens tested under anisotropic conditions, I realized i) the peak-force is reached at different stress rates ii) the post-peak curve falls more steeply for small confining pressures. The Young's modulus from directional loadings was plotted versus maximum load (Pmax) of each specimen to examine their elastic response.

Tested rock specimens from different directions (Type-1 and Type-3) have related to different signatures of fracture phenomena. This thesis work have investigated the two phenomena using a modelling code embedded in the PFC2D software code. The focus was on producing the fracture propagation paths for all specimens tested in uniaxial compressive strength (UCS) and triaxial compression test to failure in the laboratory at 5MPa, 10MPa, 15MPa, 20MPa, and 25MPa confining pressures for Type-1 and Type-3 samples. All fracture paths were modelled using the distinct element method. The applied code accounts for a realistic distribution of stress hetetrogeneties in the microstructure of the tested rocks. The crack orientation and magnitude of propagation is analyzed based on anisotropy.

I focused much of my thesis on understand the relationship between anisotropy and rock fabric patterns for each tested sample.

2 Materials

Samples used in my experiment come from three different continents, Europe, Asia and Africa. The respective countries of samples origin are Czech Republic, Japan, South Korea and South Africa. For the purposes of this research, I collected sedimentary rock sample (Kimachi sandstone) from Japan, granodiorite rock sample (African granodiorite) from South Africa, a granitic rock from South Korea (Korean granite) and a metamorphic rock sample, gneiss from Dolni Rozinka in the Czech Republic. Samples were collected from range of depths. In the sedimentary rock, the paleocurrent was determined, depositional pattern and metamorphic direction were documented for both granitic and metamorphic rock samples.

Kimachi sandstone

Kimachi sandstone is deposited in the southern coast of Shinji Lake, shimane Japan. It is medium–grained tuffaceous sandstone of the Miocene Omori formation. The sandstone is heterogeneous in its lithofacies. This sandstone has been deposited to a thickness of about 2000 m., had been deposited in a so-called “Shinzi geosynclines” during the Miocene age. Its kinetic properties are supposed to have built up from andesitic fragments with zeolith composite. Figure 1 shows a representative block diagram of Kimachi sandstone used for laboratory analysis. The direction of the paleocurrent is indicted at the top of the rock block and the bedding planes represented in horizontal blue lines.

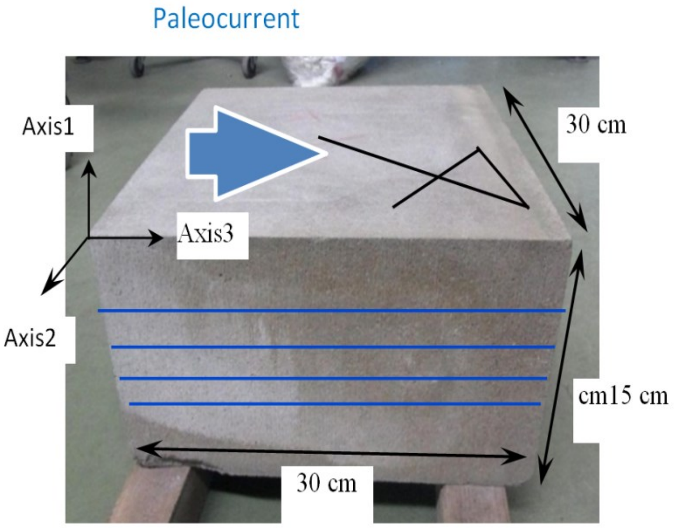


Figure 1: Rock block of Kimachi Sandstone, blue arrow at the top indicate direction of paleocurrent, horizontal blue lines shows laminations.

African granodiorite

The sample originally comes from Rustenburg, South Africa and the principal geology of its formation is the Bushveld complex. It has been formed under high temperature conditions and crystallizes as a plutonic rock. It is very hard crystalline igneous rock, gray to pink in color. This rock block has cooled slowly from molten magma deep within the earth crust with silicate minerals forming the major proportion of aggregate minerals. It consists of feldspars, quartz, dark iron-magnesium silicate minerals and feldspathic pyrozenite. The rock shows large crystal grains which are not perfectly joined together and exhibit inherent microcrack. A representative diagram is shown in Figure 2.

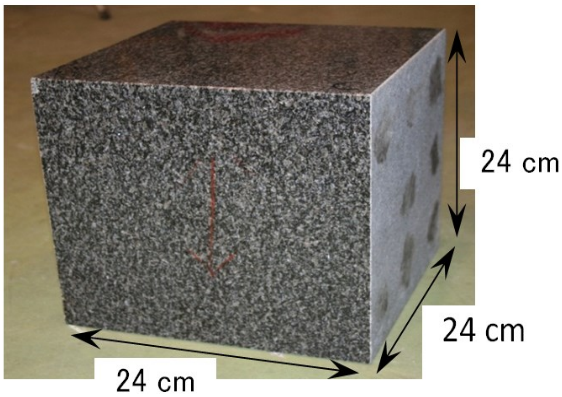


Figure 2: African granodiorite rock block..

Korean granite

This rock come from the Southern half of the Korean Peninsula and is composed geologically of a Precambrian formation. The Precambrian basement composed mostly of granite in the northern region. The isotopic age dating of this rock indicate that the Precambrian age range from about 300 to 800 ma. Three groups of granites are distributed in the peninsular that is, the Triassic granite series, Jurassic granite series and cretaceous granite series. The rock block used belongs to the Triassic granitic series. The deposit of this rock occurs as intrusions and is being emplaced in a belt shape. The mineral deposit related to this series is many hypothermal to mesothermal Au-type quartz's veins known as Korean-type gold vein. Photographic image of the rock block is shown in Figure 3.

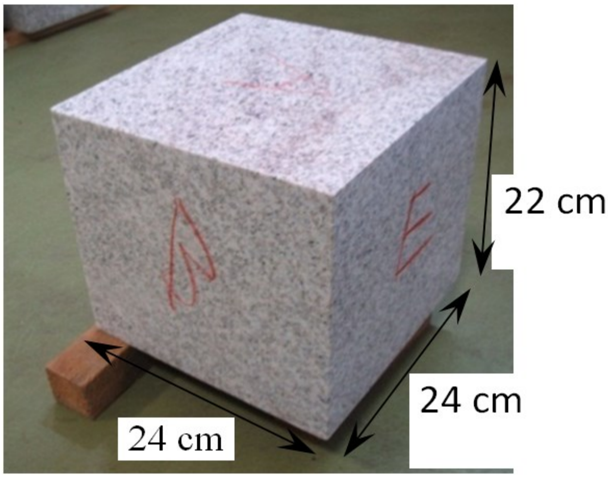


Figure 3: Korean granite rock block.

Gneiss from Dolni Rozinka

The amphibolitic gneissic rock (Fig. 4) comes from Dolni Rozinka in the Moravian region in the Czech Republic. The metamorphic rock sample is localized in a formation of metamorphosed sedimentary-effective rock of Precambrian age mostly carboniferous sediments, nowadays mostly gneisses. Taking a brief look at its geology, we can say that the wallrock are biotite –and hornblende gneisses with abundant intercalations of ortho- and paraamphibolites quartzites and marbles. It is straightforward that the deposition of this rockblock has been influenced by the mineral composition of the surroundings rocks and their physical - mechanical properties. The rock block has been formed by intensively metamorphosed rocks under high temperature and pressure conditions.

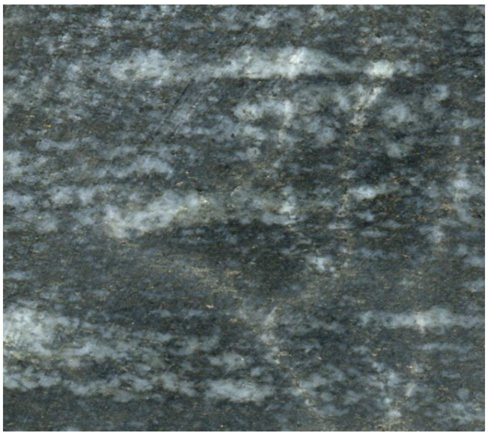


Figure 4: Rock block of Gneiss from Dolni Rozinka, Czech Republic.

3 Methods

Iintercept method.

The method of grain counting was emplyed to estimate the grain size orientation at each plane on a rock block.

I was able to determine the distribution and present the results in an aspect ratio using the method discribe in Figure 5.

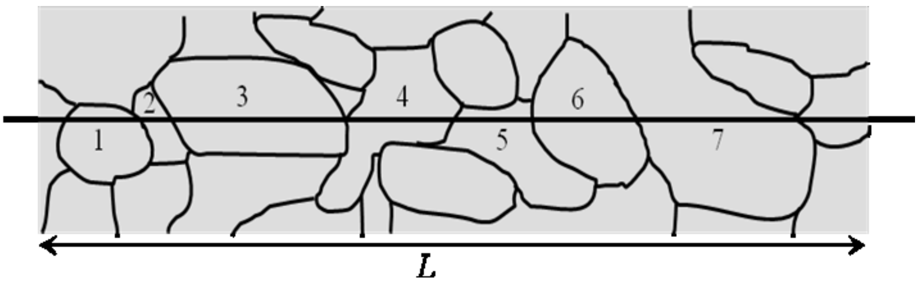


Figure 5 :Illustrative diagram of the intercept method

Ultrasonic wave method

The dissertation work emplyed the ultrasonic wave investigation method as a means of understanding the propagation of inherente microcracks within the rocks. The schmeatic diagram on how the process was conducted is shown in Figure 6.

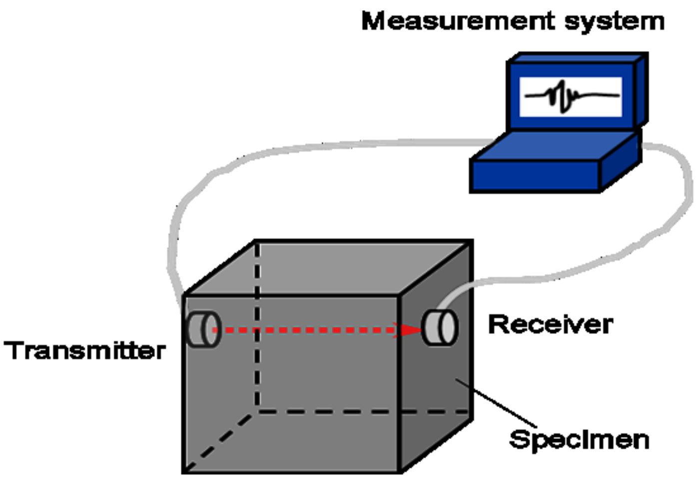


Figure 6: Schematic diagram of ultrasonic measuring machine

Uniaxial compressive strength method

Understanding the anisotropic influence to UCS response is crucial as it is one of the most integral part rock engineering. The uniaxial compressive strength of rocks, are known to be dependent on material structure. Therefore, it is important to know the anisotropy of mechanical properties of rock materials using uniaxal compression test for the design and safety of underground construction. The linkage of UCS results to selected rock types is robust in the evaluation of rocks strength properties since I could be able to present a relationship between normal stress and shear stress.

Due to rock anisotropy, fracture properties are inconsistence. The fracture behavior in rocks is very important for the design of mines and rock engineering projects. In the application of carbon dioxide capture and storage (CCS) in deep underground or high-level nuclear waste have been actively studied. Therefore, the need to understand the effect of earthquakes and how to sustain the stability of these structures for a long time is an important issue. But rocks used for the construction of these structures are usually anisotropic with distinct features like bedding planes, microcracks and so on. Hence, it is difficult to understand the precise fracture properties. Therefore, this work will present a concise discussion of the influence of anisotropy on fracture properties of selected rocks under UCS test. Figure 7 shows an uniaxial compression test specimen under test.

Figure 7: Uniaxial Compression test.

Brazilian test (splitting tensile strength)

The Brazilian test is a simple indirect testing method to obtain the splitting/tensile strength of materials such as rocks. In this test, a thin circular disc is diametrically compressed to failure. The geometry of the specimen used for laboratory experiment is shown in Figure 8. The specimen is cored from a block and requires simple processing. The indirect tensile strength is typically calculated based on the assumption that failure occurs at the point of maximum tensile stress, i.e., at the center of the disc. For this thesis, the tensile strength is represented as St and is calculated based on equation (1), which calculate the splitting tensile strength based on the Brazilian test as recommend by ISRM 1978.

$$S_t = \frac{2P}{\pi dt} \qquad (1)$$

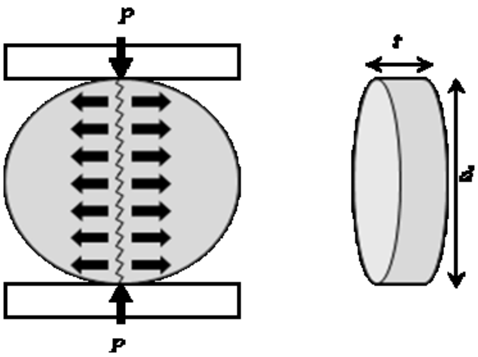


Figure 8: Schematic Diagram of a Brazilian Test Specimen.

Fracture toughness anisotropy of tested rocks

A very concise correlation of microcrack density and microcrack length and fracture toughness has been demonstrated. This study further revealed that a combination of microcracks orientation, grain size and rock lamination and foliation in metamorphic rocks can affect the fracture toughness of rocks. The grains orientation pattern has the basic influence in the fracture pattern of a rock material. The effect of anisotropic nature of coal on fracture toughness has been studied both experimentally and analytically. Conclusions made from the study were, fracture toughness was higher when measured orthogonal to bedding plane and was lower for crack propagation along bedding plane.

In this part of my thesis, the fracture toughness of two types of granites was estimated under various water vapor pressures and its dependence on the water vapor pressure of the surrounding environment was examined. Furthermore, fracture process of rocks, namely crack initiation and propagation was considered on the basis of analyzing the geometry of fracture observed. The relationship between fracture process and microstructures and grain density propagation in rocks was discussed. The fracture toughness of mode 1 K_{IC} is represented by the following equation 2.

$$K_{\mathrm{IC}} = \frac{P_{\max}\sqrt{\pi a}}{2rt} Y_{\mathrm{I}} \qquad (2)$$

Influence of rock anisotropy on the brittle-ductile behavior of tested rocks

The conventional triaxial compression and “keeping axial load and confining pressure constant” after post-peak were carried out for selected rocks (Kimachi sandstone and African granodiorite) and results were analyzed on cylindrical samples. The understanding of failure process and the post-peak behavior of rocks under confining pressure is an important aspect in rock engineering. Results shows that the post-peak axial deformation changed as the confining pressure increased from 5-25 MPa. Using the data, the strength and failure characteristics of both rocks were discussed using the Mohr-coulomb failure criterion represented for tested specimens at different orientations. For this data the parabolic failures envelop was used. The peak strength was directly related to different loading. However, the stress-displacement curves show a clear relationship with confining pressure to micro-cracks compaction and elastic response. The falure mode for the two rocks have shown mixed tensions and shear fracture(single shear fracture to) to shear fracture with double slippage planes. Finally, I estimated the cohesion(c) and frictional angle (ϕ) from each Mohr-coulomb and made strength comparison to verify the anisotropy. Results obtained from estimating the cohesion and frictional angle using triaxial compression test were then compared to obtained cohesion and frictional angle from parameters of UCS, TS and KIC from chapter 6. Figure 9 shows the MTS used for triaxial test.

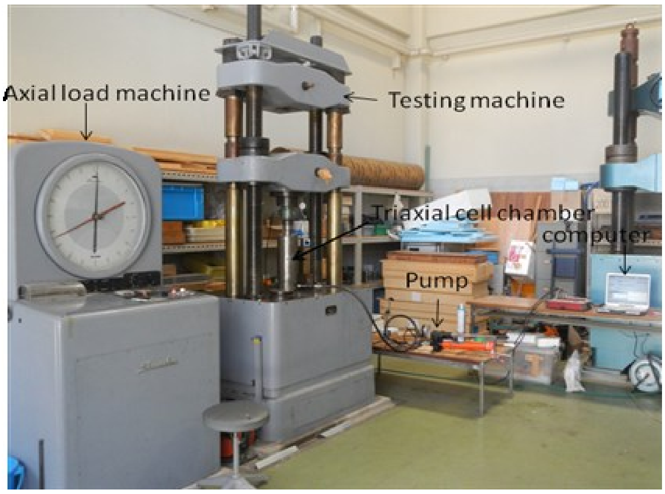


Figure 9: MTS triaxial machine and accessory components used during the test.

4 Laboratory results

The laboratory results on grain size orientation for each rock block on orthogonal planes is shown in the tables.

Table 1: Distribution of average grain diameter according to orientation for kimachi sandstone

Axes	Average grain diameter	Aspect ratio
Axis-1	0.44	1.06
Axis-2	0.42	1
Axis-3	0.52	1.25

Table 2: Distribution of average grain diameter according to orientation for African granodiorite

Axes	Average grain size diameter	Aspect ratio
Axis-1	0.71	1
Axis-2	0.72	1.02
Axis-3	0.82	1.16

Table 3: Distribution of average grain diameter orientation for Korean granite.

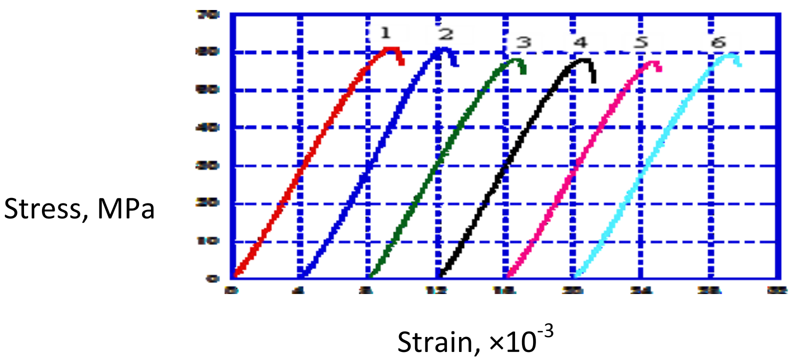
Axes	Average grain diameter	Aspect ratio
Axis-1	0.71	1.1
Axis-2	0.64	1
Axis-3	0.72	1.12

Table 4: Table 4: Distribution of average grain diameter orientation for gneiss from Dolni Rozinka.

Axes	Average grain diameter	Aspect ratio
Axis-1	0.35	1
Axis-2	0.3	1.18
Axis-3	0.29	1.23

Uniaxial compressive strength

Summary of the results for Uniaxial compressive strength in shown in figure 10a and 10 b.



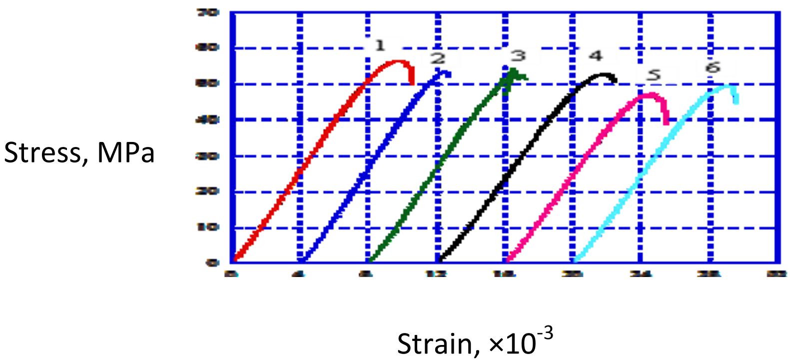
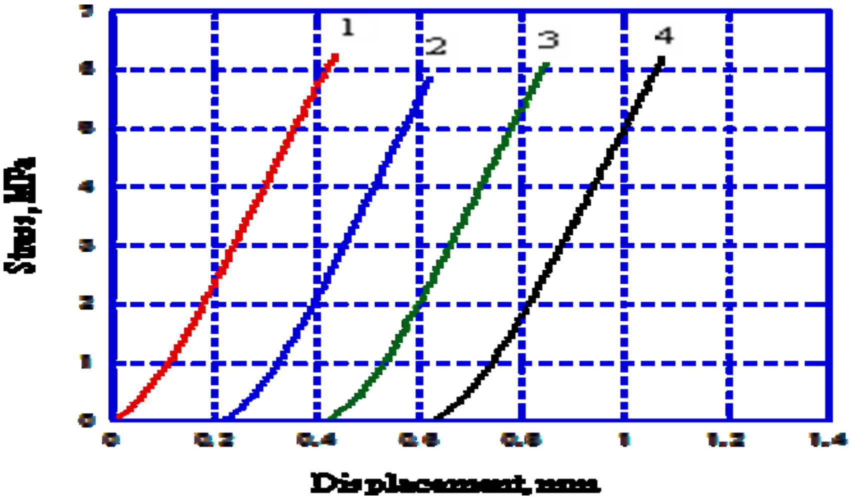


Figure 10a and 10b: Results for Uniaxial strength test.

Brazilian test

Results and conditions for Brazilian test are shown in Figure 11a and 11b.

Type-1(a)



Type-3(b)

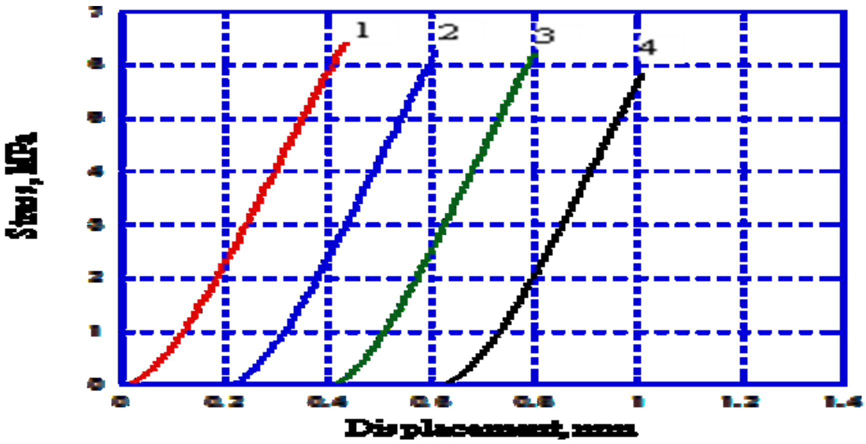


Figure 11a and 11b: Load-Displacement curve of Kimachi sandstone under tensile test Type-1(a) and Type-3(b).

Fracture toughness.

The results and conditions for fracture toughness are shown in figure 12a and 12b.

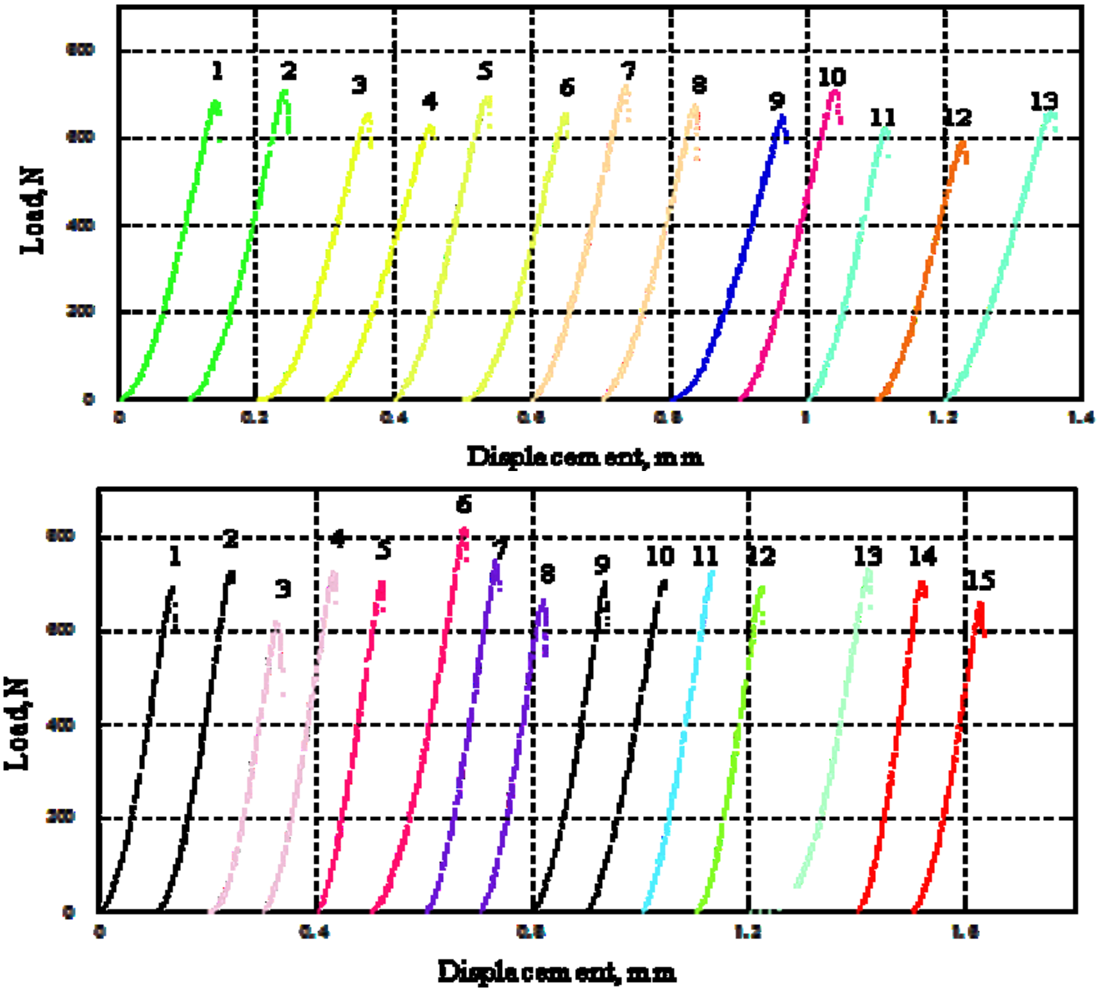
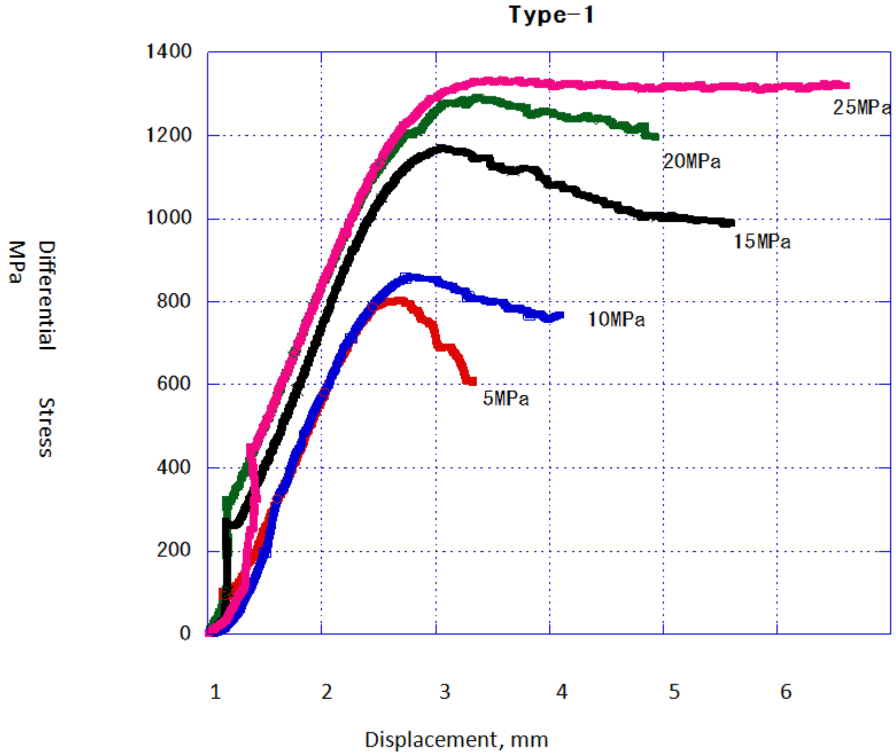


Figure 12a and 12b: Load-displacement curves of Kimachi sandstone.

Results and conditions of trixial test

The results and conditions for triaxial test are shown in Figure 13a and 13b.



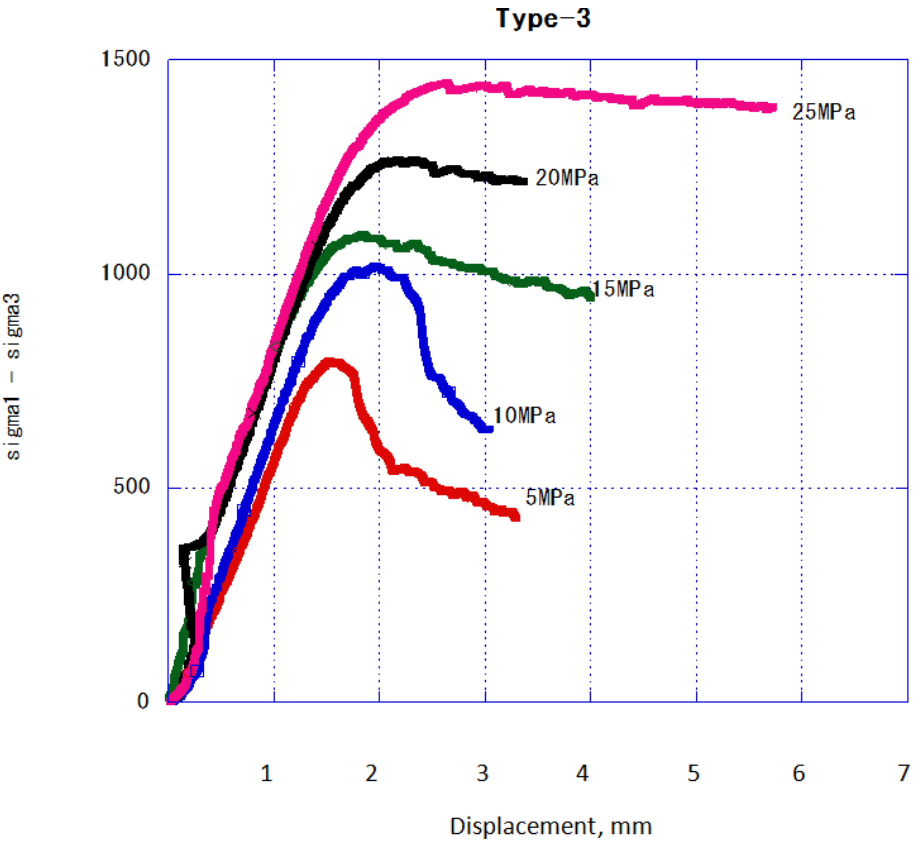
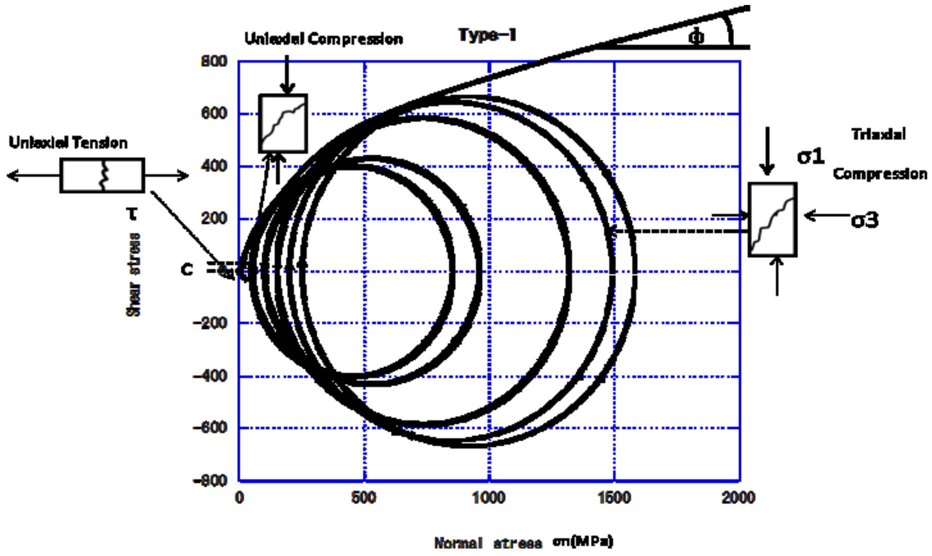


Figure 13a and 13b: Load-displacement curves of Kimachi sandstone.

The data obtained from triaxial test measurement was then used to determine the cohesion and fractional angle for all tested specimens and to understand their variation in anisotropy as shown in figure 14a and 14b. These two parameters identify the heterogeneities existing within the rock material. With this approach, I clearly approach the idea of understanding cohesive properties within a rock mass and their influence in rock fracture patterns.



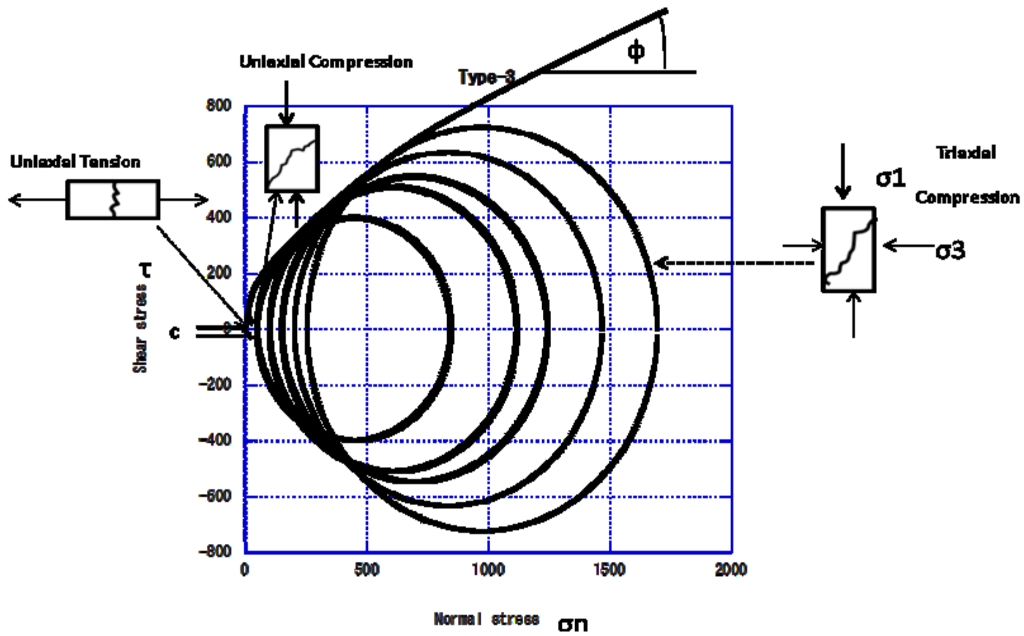


Figure 14: Representative Mohr Cicrcles of failure for Kimachi sandstones, type-1(a) and type-3(b).

Numerical simulation using Distinct Element Method (DEM)

This thesis further used measured micro and macro parameters from traixial test to simulate fracture propagation patterns of specimens tested under confining pressures. A result of simulated fractures for a confining pressure of 25MPa is shown in Figure 15.

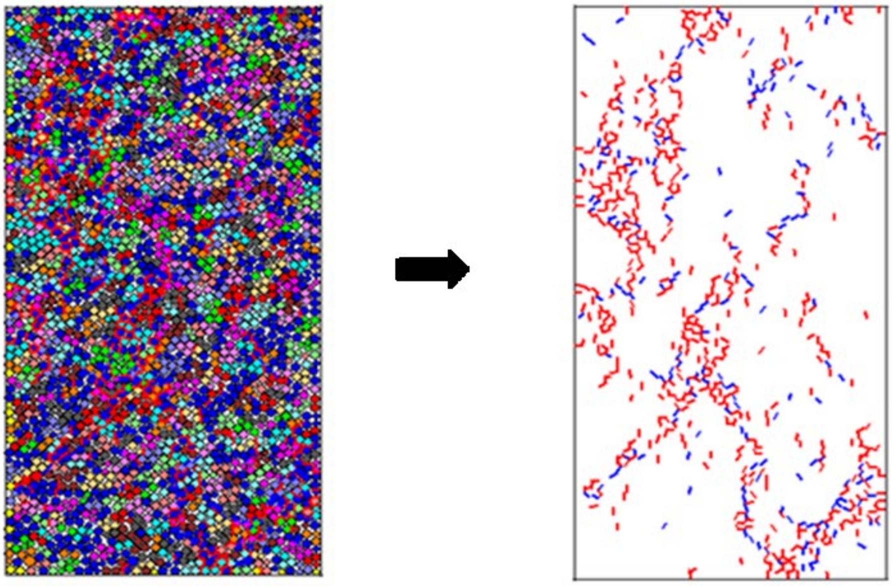


Figure 15: Specimens after test and cracks for African granodiorite.

5 Discussions

The principal objective in this study was to assess the anisotropic character of selected rock types. Various analysis like, grain diameter orientation, micro-cracks orientation(for granites), elastic wave velocity, uniaxial compressive strength(UCS), splitting tensile strength(St), fracture toughness test, traiaxial compressive test and permeability test were conducted. Samples were chosen from different localities with different conditions. The sedimentary samples were selected for their laminated properties, the granitic for their inherent microcracks and brittleness and metamorphic for its foliations in preferred orientation. However, detailed studies of their grain size distribution and elastic wave propagation have revealed them to be quite anisotropic. The study on the grain diameter orientation has shown that, the grain diameter orientation on Axis-3 for all estimated rock types is larger and straighter when compared to other directions. The average grain diameter for each rock are, Kimachi 0.44 - .52, African granodiorite 0.71 – 0.82, Korean granite 0.71 – 0.72 and Gneiss from rozinka 0.51 – 0.62. This shows that the distribution of grains of these rocks is not even. Results of elastic wave velocity measurement have supported this uneven distribution of grains. Kimachi sand sandstone has shown higher values of elastic waves in the Axis

1 direction. This shows that there is a greater compaction of grains in this direction and air filled pore contribution. This phenomenon has like to occur during rock deposition and has created anisotropic property for the studied rock.

On the other hand, it will be difficult to attribute the anisotropic elastic wave property in granitic rocks to grain size distribution but rather micro-cracks orientation and distribution. The propagation of elastic waves for the two granites is higher in Axis-1 than in the other directions. This means, there is high density of micro cracks oriented to the Axis-1 direction. This micro cracks are filled with air and have lowered the velocity of elastic wave velocity. Corresponding elastic wave properties for all rocks are, Kimachi, Axis-1 2640 m/s, Axis-2 2590 m/s, Axis-3, 2580 m/s, African granite, Axis-1 6760, Axis-2, 6580, Axis-3 6540, Korean granite, Axis-1, 3990, Axis-2, 3850, Axis-3, 3640. In the two granites, the alignment of the micro cracks is not as directional but their densities have played a role in influencing their anisotropy.

In considering the study of uniaxial compression, examples of stress-strain curves obtained in uniaxial tenson test (for all samples) are shown in chapter 2. The specimens have demonstrated physio-mechanical properties of selected rocks. The average uniaxial compressive strength of all tested rocks is, Kimachi, 55.1, African granite, 241.5, Korean granite, 181.65 and Gneiss from Rozinka, 114.35. The relationship between uniaxial compressive strength for Type-1 and Type-3 specimens for all specimen is anisotropic when compared. The experimental results can be explained as follows. The distribution of grains in the kimachi sandstone is not even, grain size orientation has shows Axis-1 to be compacted. Specimens from this direction have shown high uniaxial compressive strength due to compacted grain to exhibit higher elastic properties. On the other hand, the distribution of micro cracks in the two granites is not random but has a preferred density orientation. There is a high density of micro cracks in the Axis-1 direction than in the Axis -3. This has shown Type-1 specimens with higher strength than Type-3. This anisotropic strength characteristic is in agreement with other physical properties like the P-wave velocities, e.g. Lin et al 2008. The strength anisotropy in gneiss is quite high for Type-1 than Type-3. This is due to the uniaxial compressive strength of this gneiss (perpendicular to foliation). There is some complicated understanding of stress-strain curves from the gneiss. This has been linked to its irregular distribution of its metamorphic structures. The anisotropic characteristic of the Young's modulus of the specimens under uniaxial compression when compared within a specimen are almost the same except for kimachi and gneiss. But when compared between specimens, there is a great difference as shown in chapter 2. Observation of fractures was also considered in analyzing the anisotropic fracture property. First, in the kimachi sandstone, the fracture propagation was influenced by the presence of laminations and this resulted to two fracture modes. The mode of fracture perpendicular to laminations has difficulty to separate, while the one parallel to lamination finds it easier for separation. I correlate the separation to tensile strains developed in uniaxial compression. The pre-existing cracks give an added advantage to splitting along laminations which is hard to develop in perpendicular direction as illustrated in chapter 2.

On the other hand, granitic rocks developed their fracture in the direction of high density micro cracks plane. This shows that fracture is propagated at micro crack tips. For all Type-1 specimens, longitudinal splitting was observed and for Type-3, longitudinal splitting and shear fracture dominanted. For the gneissic rock samples, the fractures are longitudinal splitting and shear fracturing based on the orientation as perpendicular and parallel to foliation.

In considering the tensile strength anisotropy, the study is to characterize the tensile strength anisotropy of the selected rock types under static loading conditions. As shown in the load-displacement curves in chapter 4, Type-1 specimens loaded in direction of Axis-1 shows higher strength of tensile splitting when compared to those in Type-3. The tensile strength anisotropy is mainly attributed to grain size distribution in the sand stone and to the distribution and orientation of micro cracks e.g. Voight et al 1969. Under loading conditions, I observed that the mean tensile splitting is lower for all specimens with a loading rate of 1.3x10-3m/s. This is because in the static test, the loading speed is very slow to allow all micro-cracks to interact. This allows the critical crack and the multiple micro-cracks to contribute to the failure of the specimen.

List of Authors Publications

KOROMA, S., ARATO, A., GODIO, A., ASUE, H. and OBARA, Y.: Analyzing the geophysical signature of a contaminated soil using electrical survey method. Japan: MMIJ journal, 2013. ISSN 1343-9898.

DEVECKA, B., MUDRON, I., BELAJ, P., DROZDOVA, M., KOROMA, S.: Using GIS technology in digital sinage. SGEM2013 Conference Proceedings, ISBN 978-954-91818-9-0 / ISSN 1314-2704, June, 16- 22,2013, vol.1, 1057-1064pp.

KOROMA et al.: Analyzing the geophysical signature of a contaminated soil using electrical survey method. Environmental Earth Sciences, March 2013 *(in processing for publication).*